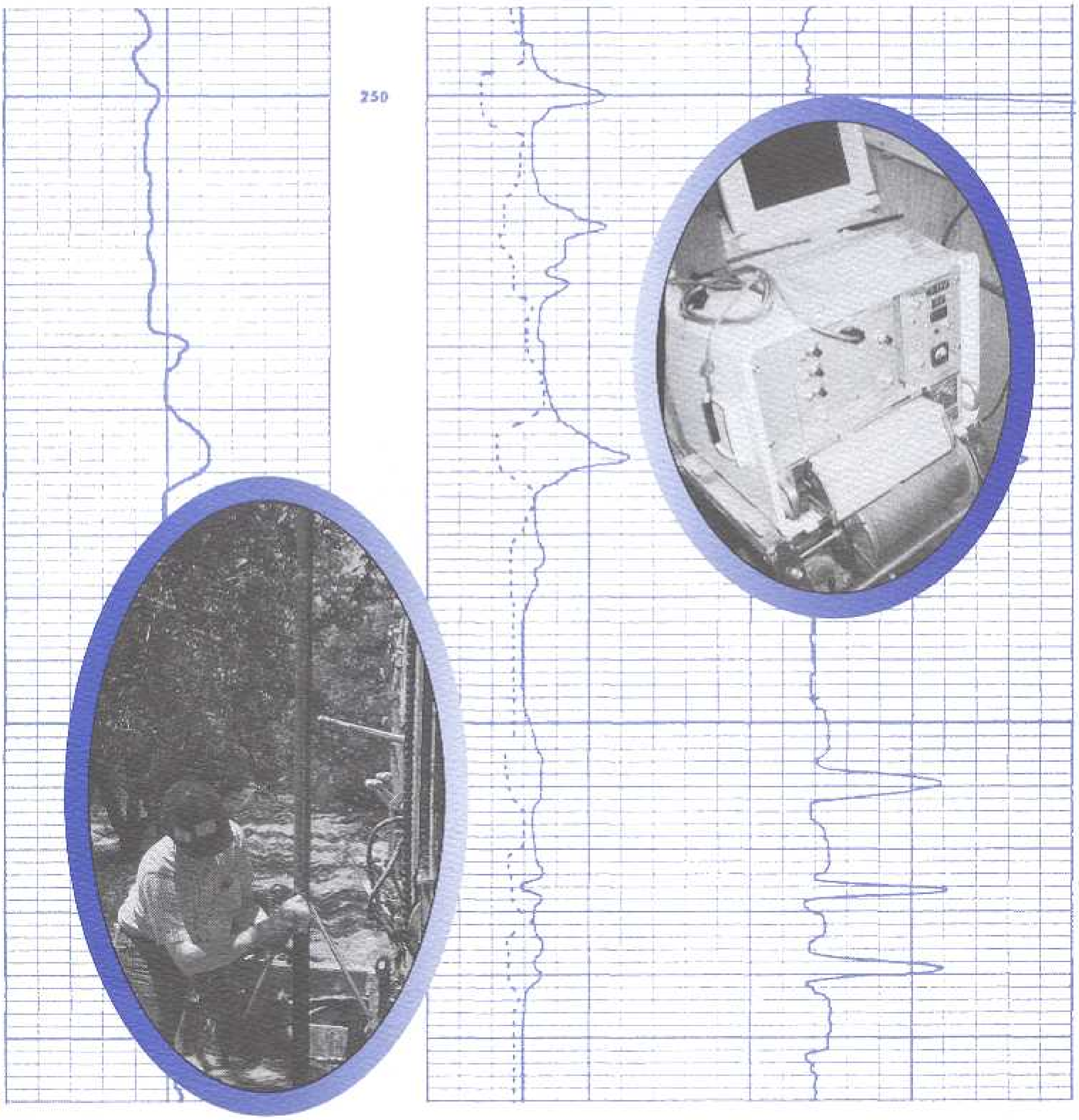
Application of Borehole Geophysics at Hazardous Substance Release Sites

Guidance Manual for Ground Water Investigations



State of California
Environmental Protection Agency

APPLICATION OF BOREHOLE GEOPHYSICS AT HAZARDOUS SUBSTANCE RELEASE SITES

Guidance Manual for Ground Water Investigations

July 1995

Pete Wilson
Governor
State of California

James Strock
Secretary
California Environmental Protection Agency

The California Environmental Protection Agency:

Department of Toxic Substances Control
State Water Resources Control Board
Integrated Waste Management Board
Air Resources Board
Department of Pesticide Regulation
Office of Environmental Health Hazard Assessment

FOREWORD

The California Environmental Protection Agency (Cal/EPA) is charged with the responsibility of protecting the state's environment. Within Cal/EPA, the Department of Toxic Substances Control (DTSC) has the responsibility of managing the state's hazardous waste program to protect public health and the environment. The State Water Resources Control Board and the nine Regional Water Quality Control Boards (RWQCBs), also part of Cal/EPA, have the responsibility for coordination and control of water quality, including the protection of the beneficial uses of the waters of the state. Therefore, the RWQCBs work closely with DTSC in protecting the environment.

To aid in characterizing and remediating hazardous substance release sites, DTSC had established a technical guidance work group to oversee the development of guidance documents and recommended procedures for use by its staff, local governmental agencies, responsible parties and their contractors. The Geological Support Unit (GSU) within DTSC provides geologic assistance, training and guidance. This document was prepared by GSU staff in cooperation with the technical guidance work group and the RWQCBs. This document has been prepared to provide guidelines for the investigation, monitoring and remediation of hazardous substance release sites. It should be used in conjunction with the two-volume companion reference for hydrogeologic characterization activities:

Guidelines for Hydrogeologic Characterization of Hazardous Substances Release Sites
Volume 1: Field Investigation Manual
Volume 2: Project Management Manual

Please note that, within the document, the more commonly used terms, *hazardous waste site* and *toxic waste site*, are used synonymously with the term hazardous substance release site. However, it should be noted that any unauthorized release of a substance, hazardous or not, that degrades or threatens to degrade water quality may require corrective action to protect its beneficial use.

This document supersedes the 1990 draft of the DTSC *Scientific and Technical Standards for Hazardous Waste Sites, Volume 1, Chapter 7*, and is one in a series of Cal/EPA guidance documents pertaining to the remediation of hazardous substance release sites.

Additional copies of this document may be obtained by ordering directly from:

Department of General Services
Publications Section
P.O. Box 1015
North Highlands, CA 95660

phone: (916) 574-2200

Orders are accepted pre-paid by mail only. Please allow at least 30 days for delivery. When ordering, please provide the title and stock number (listed below), and your check or money order. Price includes UPS delivery. Prices are subject to change without notice. Please call General Services for current price and availability.

Title: Application of Borehole Geophysics at Hazardous Substance Release Sites   Stock No. 754 095 810 348

ACKNOWLEDGEMENTS

The preparation of this guidance document was achieved through the efforts of many individuals. The following people had primary responsibility for writing and editing:

Bill Owen	Hazardous Substances Engineering Geologist,
Steve Belluomini	Supervising Hazardous Substances Engineering Geologist I.

Members of the technical guidance work group participated in the development of this document by providing comments and direction. Additional review and comments were provided by the Regional Water Quality Control Boards and Dennis Parfitt of the State Water Resources Control Board. We thank them for their cooperation and helpful suggestions.

Finally, thanks are extended to the staff of the Geological Support Unit and to the many anonymous reviewers outside DTSC, whose comments were indispensable for completing this document.

TABLE OF CONTENTS

TABLE OF CONTENTS
(CONTINUED)

ILLUSTRATIONS | **PAGE**

ABBREVIATIONS AND SYMBOLS

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
d_h	borehole diameter
d_i	flushed zone diameter
d_j	invasion zone diameter
DTSC	Department of Toxic Substances Control
h	bed thickness
h_{mc}	mud cake thickness
QA/QC	Quality Assurance and Quality Control
R_m	mud resistivity
R_{mc}	mud cake resistivity
R_{mf}	mud filtrate resistivity
R_s	adjacent bed resistivity
R_t	true formation resistivity
R_{xo}	flushed zone resistivity
R_w	formation water resistivity (undisturbed zone)
SP	spontaneous potential
S_{xo}	flushed zone water saturation
S_w	water saturation (undisturbed zone)

1 INTRODUCTION

1.1 Purpose

The following document has been written to provide guidelines for the application of borehole geophysical techniques in the characterization of hazardous waste sites. The purpose of this document is to aid in the selection of borehole geophysical tools, provide recommended quality assurance and quality control (QA/QC) procedures, and standardize presentation of the resulting data. The recommendations presented here represent the minimum criteria necessary to obtain quality data and assure reasonable and independently verifiable interpretations.

As of this writing, other professional organizations are also developing guidelines for borehole geophysical techniques. Most relevant of these organizations are the American Society for Testing and Materials (ASTM) and the American Petroleum Institute (API). We recognize that guidelines developed by a general consensus (such as the ASTM balloting process) are often preferred by the regulated community. It is the intent of the California Environmental Protection Agency (Cal/EPA) to incorporate these other guidelines, where technically and legally relevant, into the Cal/EPA guidance framework. Cal/EPA is striving to keep up to date on the development of external guidelines, and every attempt has been made to incorporate the intent of those documents into the Cal/EPA guidelines. As new techniques gain acceptance and existing techniques are refined, this guidance document will be updated accordingly to meet the state of the science.

The recommendations presented here are a subset of the larger site characterization process. The additional investigative tools necessary to adequately characterize a site, as well as the conditions where borehole geophysics should be applied, are outlined in the main body of this document.

1.2 Application

Borehole geophysical techniques provide an efficient and cost-effective means to collect lithologic and hydrologic information from wells and borings. These methods provide continuous measurements of physical properties along the entire length of the borehole, supplementing the discrete information gathered by coring. Perhaps the most concise explanation of the advantages of borehole geophysics was put forth by Keys (1989):

> *The most important objective of borehole geophysics is to obtain more information from a well than can be obtained from drilling, sampling and testing. Drilling any kind of a test hole or well is an expensive procedure. The test hole or well provides access to the ground water system at one point; therefore, each test hole or well provides a valuable opportunity to obtain vertical profiles or records of many kinds of data. The cost-benefit ratio for recording geophysical logs usually is quite favorable. That is why all oil wells drilled anywhere in the world are logged. Although the unit costs for drilling most water wells are less than those for drilling oil wells and the value of the product usually is less, the cost of logging usually also is less.*

By calibrating the geophysical response with the data obtained from a representative number of continuously cored holes, the amount of coring needed to characterize a site can be substantially reduced, with a corresponding reduction in cost.

1.3 Limitations

The recommendations presented here represent the minimum criteria necessary to assist in obtaining quality data and assuring reasonable and independently verifiable interpretations. Some sites may require borehole geophysical studies above and beyond the scope of this document, while at other sites a less rigorous application of this guidance may be appropriate. It is the obligation of the responsible parties and the qualified professionals performing site investigations to consult with pertinent regulatory agencies, identify all requirements and meet them appropriately.

It is not the purpose of this document to define operating procedures for conducting borehole geophysical logging or for interpreting the results. This responsibility rests on those performing the work. The qualified professional in charge of the field investigation must specify the operating procedures in an appropriate work plan and document any significant departures from the work plan that were necessary during the course of the investigation.

This document does not supersede existing statutes and regulations. Federal, state and local regulations, statutes, and ordinances must be identified when required by law, and site characterization activities must be performed in accordance with the most stringent of these requirements where applicable, relevant and appropriate.

2 RECOMMENDED PRACTICES AND SPECIFICATIONS FOR BOREHOLE GEOPHYSICS

2.1 Personnel Qualifications

When discussing the qualifications of personnel interpreting geophysical logs, it is necessary to distinguish between qualitative and quantitative interpretation. **Qualitative** interpretation involves the identification of different soil and lithologic types by comparing the general response of the logging probes from borehole to borehole. This type of interpretation is common in environmental studies. **Quantitative** interpretation uses the numerical data provided by the logging probes to define the physical parameters of the soil and rock types encountered by the probe (e.g., clay/shale volume, density, porosity). Quantitative interpretation is not routinely performed in environmental studies, but its use may increase as algorithms for freshwater aquifers are refined. Keys (1989, pages 13 through 16) provides a good discussion of qualitative and quantitative interpretation.

Under the Geologist and Geophysicist Registration Act, personnel interpreting borehole geophysical data are required to be registered to practice geology or geophysics in the state of California; if not registered, these personnel must be overseen by a registered geologist or geophysicist who accepts responsibility for the interpretations. This registered professional must accept responsibility for the work by signing any reports containing borehole geophysical proposals or interpretations and providing an appropriate proof of registration (usually his or her Registration number).

Very few geologists or geophysicists have any significant formal training in the interpretation of geophysical logs. In environmental geology, experience is typically acquired on the job. The exceptions are **log analysts**: earth scientists specifically trained in the art and science of geophysical logging. The State currently has no specialty certification for log analysts. Therefore, in addition to appropriate proofs of registration, the registered geologist or geophysicist who signs any report containing borehole geophysical proposals or interpretations should provide additional evidence of experience, by attaching a summary of pertinent experience. For qualitative log analysis, a minimum of two years' experience in log interpretation is recommended. For quantitative log analysis, the recommended length of experience is three years.

2.2 Quality Control Parameters for Geophysical Logging

Documentation

Procedures for quality assurance and quality control for borehole geophysical logs should be addressed in an appropriate site characterization workplan and final report. The workplan should outline the rationale for the selection of the basic logging suite and identify the objectives of the study. The final report must present the interpreted results of the geophysical logs and discuss any problems encountered in the field and any deviations from the workplan needed to solve those problems.

Both logging procedure and hole information must be recorded in order to adequately interpret borehole geophysical data (Keys, 1989). Such information must be documented on the well log (commonly referred to as *header information*; see Table 1).

As with surface geophysical techniques, borehole logging is susceptible to interference due to equipment malfunction, electromagnetic radiation and borehole conditions (collectively referred to as noise). Fortunately, borehole geophysical noise is usually less problematic compared to noise associated with surface surveys. However, the effect of noise on borehole logging must be assessed and appropriate measures taken to reduce any undue influence. Any interference on a geophysical log, and procedures used in correcting such interference, should be documented on the actual log or in the final geophysical report.

Calibration and Field Checks

The quality of the instrument response needs to be assured through regular calibration and by conducting field checks prior to each survey. All logging probes should be tested and calibrated on a regular basis, as appropriate for each probe. Testing and calibration should take place according to the manufacturer's recommendations, or should follow the guidelines presented in the United States Geological Survey Water Resources Investigation Report 88-4058 (Hodges, 1988). In addition, all logging probes should be field checked and recalibrated as necessary at the beginning of each field day.

Calibration and field-check information for any particular logging probe should be documented on the borehole log for that instrument.

The potential for operator or instrument error needs to be evaluated on a regular basis. When logs will be used for qualitative analyses, this requirement may be met by careful observation of the logs while they are being run and by calibration and daily field checks. However, when quantitative analyses are needed, the probes must be checked with an appropriate standard both before and after the probes are run in the hole. Field checks can be made by using built-in standards, external calibration tools, or even a known reference within the borehole (e.g., casing). In any event, at least two standards must be available for each probe so that both scale position and sensitivity can be checked (Keys and MacCary, 1983). The type of field standard used and the values obtained from the field checks should be recorded on the appropriate log.

Of increasing prevalence in hydrogeologic logging is the use of internally-calibrated probes. For these probes, calibration adjustments occur automatically during logging, making the standard "before-and-after" field checks useless. Instead, a continuous indicator or summary of calibration values from a log run is needed in addition to a record of the most recent shop calibration. The API is considering three possible solutions to this problem: 1) a continuous log of calibration values, 2) flagging log intervals where calibration is outside an acceptable range, and 3) a statistical summary of calibration changes. As of this writing, this issue has not been resolved within the API. Presently, any of these presentation formats are acceptable, provided both the most recent shop calibration data and the range of permissible calibration values are provided in the **calibration block** (a section of the log header that presents tool calibration data).

Logging Speed

The choice of logging speed is an important factor in assuring data quality. Since logging speed affects resolution, the choice of logging speed must be appropriate to the data needs and the type of probe used for each log. It is not possible to define maximum logging speeds for every technique--logging speed is influenced by data requirements and is tool-specific. The exceptions to this rule are the nuclear logs. Maximum logging speeds for nuclear logs are discussed in Section 2.5.3.

Hole Location and Reference Elevation

Hole location and depth of measurement are important factors in quality control. All hole locations (both exploratory borings and wells) must be located with reference to a permanent datum. The starting depth of the log should also be referenced to the elevation of a permanent datum. For lithologic control, elevations derived by simple sighting from a nearby benchmark may be all that is needed; however, accuracy of location survey data must be based on the site-specific objectives of the investigation. Detailed surveying, if necessary, should be performed by a licensed surveyor for the state of California. If a hole or well will be logged periodically over

WELL INFORMATION

Well Name/Number
Location/Site Name
Surface Elevation
Casing Height (above surface)
Depth Reference (description)
Borehole Diameter
Casing Information (Type, Diameter, Location)
Drilling Fluid Description (Type, Resistivity, Temperature)
Level of Fluid in Borehole or Well at Time of Logging
Construction Information (Locations and composition of annular seals, filter pack and screen)
Drilling Information (Date Drilled, Name of Driller, Drilling Method, Drilled Depth)

LOG INFORMATION

Type of Log
Run Number
Name(s) of Operators, Observers
Date Logged
Probe Description (Name, Serial Number)
Logging Speed
Recorder Scale
Module/Panel Settings
Calibration Data
Listing of all other logs run on same date

MISCELLANEOUS INFORMATION

Additional comments (e.g., adverse weather, logging conditions, any irregularities in calibration, logging procedure)

Table 1. Log header information required for all borehole geophysical logs. Header information must be as complete as possible. Missing information must be so noted on the header form. (After Keys, 1989).

time, starting depths should be referenced to a marker permanently affixed to the surface completion.

Repeat Logs

An additional quality control check is the **repeat log** (that portion of the hole that is logged twice to check instrument function). Every log should be rerun either partially or entirely, depending on the judgement of the field personnel. When partially repeated, the repeated portion of the log should span an interval of maximum signal variation and any intervals of particular interest to the study. For the sake of economy, the necessity of additional reruns should be evaluated during the actual logging, while the logging equipment is on-site. Repeat logs should be documented and the logs included in the site characterization report.

Depth Correction

With many borehole techniques, it is possible to record several measurements simultaneously through the use of combination probes. Where combination probes are used, the borehole measurements should be corrected for differences in measuring depth between the tools; this correction should be noted in the header. The correction may be automatic, or may be performed by manually shifting the responses of the accessory logs to align with the primary log (usually an electrical log).

2.3 Presentation of Geophysical Logs

Header Format

The header information outlined in Section 2.2 must be presented in a uniform fashion. The API has developed guidelines RP 31 and RP 33 that contain standardized headers for electrical and nuclear logs (American Petroleum Institute, 1967 and 1974). These headers were developed for oil well logging, and although they may not be entirely applicable for environmental logging, they are acceptable standard header formats. An alternative to the API formats is the abbreviated version presented in Figure 1. Most companies that perform environmental logging have some variation of these formats. In short, an acceptable header should contain spaces for the header information from Section 2.2 and follow the general format of the example referenced in Figure 1.

Log Format

Final copies of geophysical logs should be presented using the three-track or two-track API format, as presented in API RP 31 and API RP 33 (American Petroleum Institute, 1967 and 1974). Figure 2 is provided for illustration. In the three-track format, Track 1 is separated from Tracks 2 and 3 by a depth track. In the two-track format, Track 1 remains the same, but Tracks 2 and 3 are replaced by a single 5-inch wide track. All tracks should have linear scales whenever possible. However, when necessary to show the range of signal variation, logarithmic scales in the appropriate tracks are acceptable.

The API, in their guidelines (RP 31 and RP 33) have long recommended that electrical logs be segregated from nuclear logs, each being presented on a separate log record. For environmental studies, an accepted and common practice has been to combine these types of geophysical logs into a **composite log** (a presentation format in which nuclear and electrical measurements are combined). In this format, Track 1 is reserved for three logs: caliper, SP and gamma. Short- and long-normal resistivity (or their equivalent) are presented in Track 2. Additional correlation logs are assigned to Tracks 2 and 3 as space permits. We feel this is an acceptable presentation format, with the following caveat: with the exception of Track 1, no more than two logs should be overlaid on the same track. For Track 1, SP, gamma and caliper logs may be overlaid simultaneously, as long as the logs are still legible. If not, then the API guidelines should be followed, and electrical and nuclear logs should be separated (caliper logs, however, may still be recorded in Track 1). If logs are overlaid, different line patterns must be used to distinguish between logs.

Repeat sections and calibration records may be presented either below the main log or on separate records. If presented separately, headers must be attached for each record.

2.3.3 Log Scale

The choice of log scales is an important factor in assuring that the data show adequate resolution without excessively amplifying noise. To present subsurface information without undue distortion, the vertical log scale should be the same for each log at a site. Most boreholes drilled for environmental investigations are no more than a few hundred feet deep; therefore, the possibility of having a log that is excessive in length is insignificant. The vertical scale must be chosen based on site-specific resolution requirements, but should not be greater than API's 5-inch log (5"=100' [1"=20']) for English units, or 1:200 log (1m=200m) for metric units (American Petroleum Institute, 1967 and 1974). Note: this recommendation does not apply to logs reproduced for the purposes of constructing cross-sections or other illustrations. Logs may be reduced for this purpose, so long as copies of the original logs are also provided.

The horizontal scale for each log should be chosen to accommodate the expected range of signal variation. For both analog and digital logging systems, the signal range can usually be measured and selected as the probe is descending the borehole (in digital systems, this process is often automatic). In the event that signal variation exceeds the expected range, or when accommodating the expected variation would degrade resolution, the log should be presented at two scales: one scale must span the entire range of variation, the other should show the necessary resolution for either the entire log or for specific zones of interest, as appropriate to the objectives of the study. For analog systems, this usually requires logging the borehole twice with the same probe; in this case the repeat log may also serve as the second run. With digital systems, however, the initial run usually contains all the

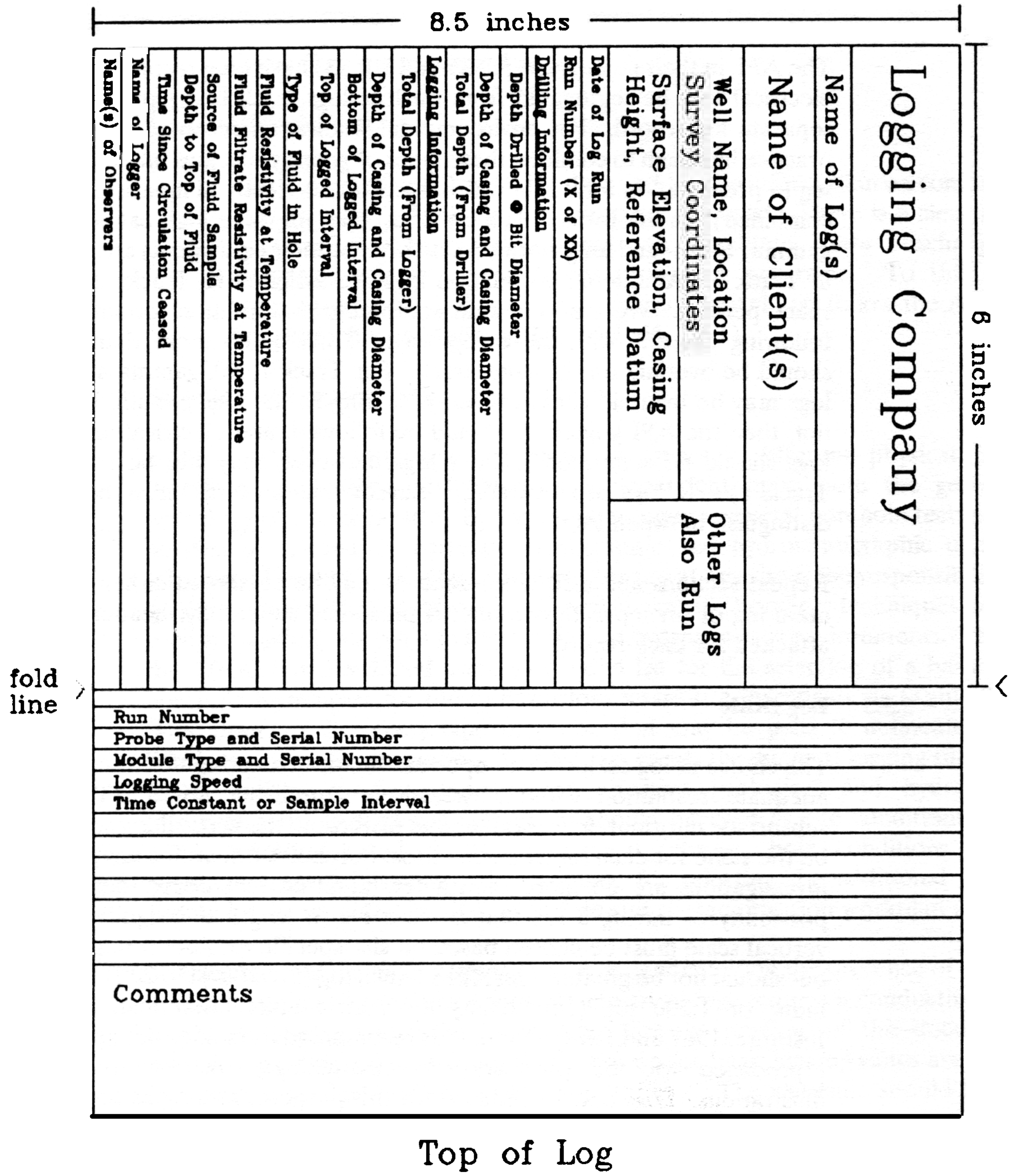


Figure 1. Schematic diagram of the format for the presentation of log header information. Where more than one data element exists (such as casing or bit size changes) these elements should be recorded on the same header line. The names of all probes and modules used during the same logging run must be recorded on the header. After Asquith and Gibson (1982) and Collier and Alger (1988).

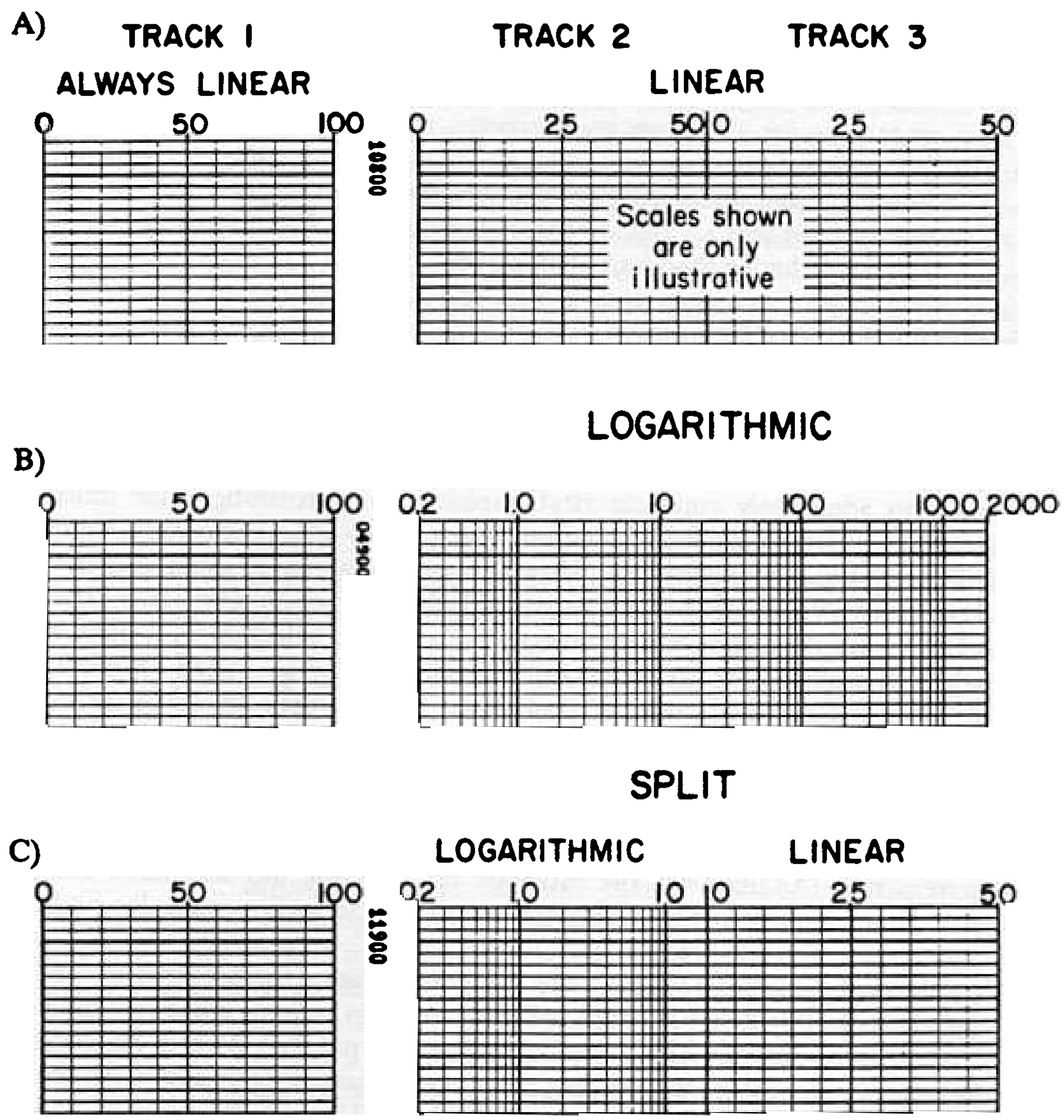


Figure 2. Example of API two-and three-track formats. A) three-track format, linear scales. B) two-track format, logarithmic scale for Track 2. C) three-track format, **split grid** (combined log and linear scales). From Schlumberger (1974).

necessary data--all that is needed is to re-print the same log (or portions thereof) at the expanded scale.

2.3.4 Digital Formats

The storage of geophysical log data and header information on computer disk or tape is, for all intents and purposes, universal. There is a clear need for a standardized digital format to facilitate data exchange and intercommunication of different processing programs. To this end, we recommend that all digital copies of geophysical logs follow the API Digital Log Interchange Standard (API RP 66, 1991).

2.4 Selection of Logging Techniques

Each borehole geophysical technique measures a different physical property; therefore, the choice of techniques is dependent upon both the geology and hydrology of a specific site. By the same argument, several borehole techniques are needed to adequately correlate stratigraphic and hydrostratigraphic units. The selection of borehole logging techniques for use at any site is the responsibility of the qualified geologist or geophysicist. However, specific borehole techniques have been used successfully for years to log a variety of hydrogeologic environments. Therefore, the DTSC has developed a recommended list for the selection of a basic suite of borehole techniques for use in hazardous waste site investigations (Table 2). This table does not list every type of probe that may be used to delineate borehole lithology or aquifer properties. This list represents the *minimal* logging suite that the DTSC judges to be adequate for effective geological and hydrogeological interpretation. Additional techniques should be used as site conditions and data needs warrant, based on the targets of interest, hole conditions and data requirements. Additionally, the rationale for selecting the additional techniques should be documented in an appropriate site characterization workplan and report.

The selection of the basic logging suite is dependent upon the presence of fluid in the borehole, primarily because almost all electrical logs require a conducting medium to channel current into the formation. For the purpose of this document, the borehole geophysical techniques that make up the basic logging suites are separated into "wet" and "dry" suites, as shown in Table 2. The wet suite should be used in liquid-filled holes, the dry suite is intended for dry holes.

The selection of the wet or dry suite for a particular boring is primarily based upon the drilling method used to create the hole. Consequently, it is necessary to distinguish between "wet" and "dry" drilling methods. The distinction is simple--wet methods use water or mud as a drilling fluid, dry methods utilize either air (with or without liquid additives) or no drilling fluid. Examples of wet and dry drilling methods are shown in Table 2.

As presented, the selection criteria are overly simplistic, because under certain conditions casing must be placed in the hole as drilling proceeds (this is usually done to maintain hole stability or, in the case of hollow-stem auguring, is inherent to the drilling technique). Therefore, it is necessary to modify the selection process to include hole casing as a secondary criterion. To this end, the flow chart in Figure 3 is presented for clarification.

A. BASIC LOGGING SUITES

Wet Suite	Dry Suite
Caliper	Caliper
Gamma	Gamma
Spontaneous Potential (SP)	Induction[3]
Point Resistance	
Shallow Electrical[1]	
Deep Electrical[2]	

B. DRILLING METHODS

Wet Methods	Dry Methods
Mud Rotary	Air Rotary
Reverse Circulation	Percussion[4]
	Auger
	Cable Tool

[1]includes short normal, shallow focused or shallow induction probes
[2]includes long normal, deep focused or deep induction probes
[3]includes shallow and deep induction probes
[4]includes down-hole hammer and casing-driver methods

Table 2. A) Minimum techniques required for a borehole logging suite. Suites may be "wet" or "dry", depending on drilling process. B) Examples of "wet" and "dry" drilling techniques. See text for discussion.

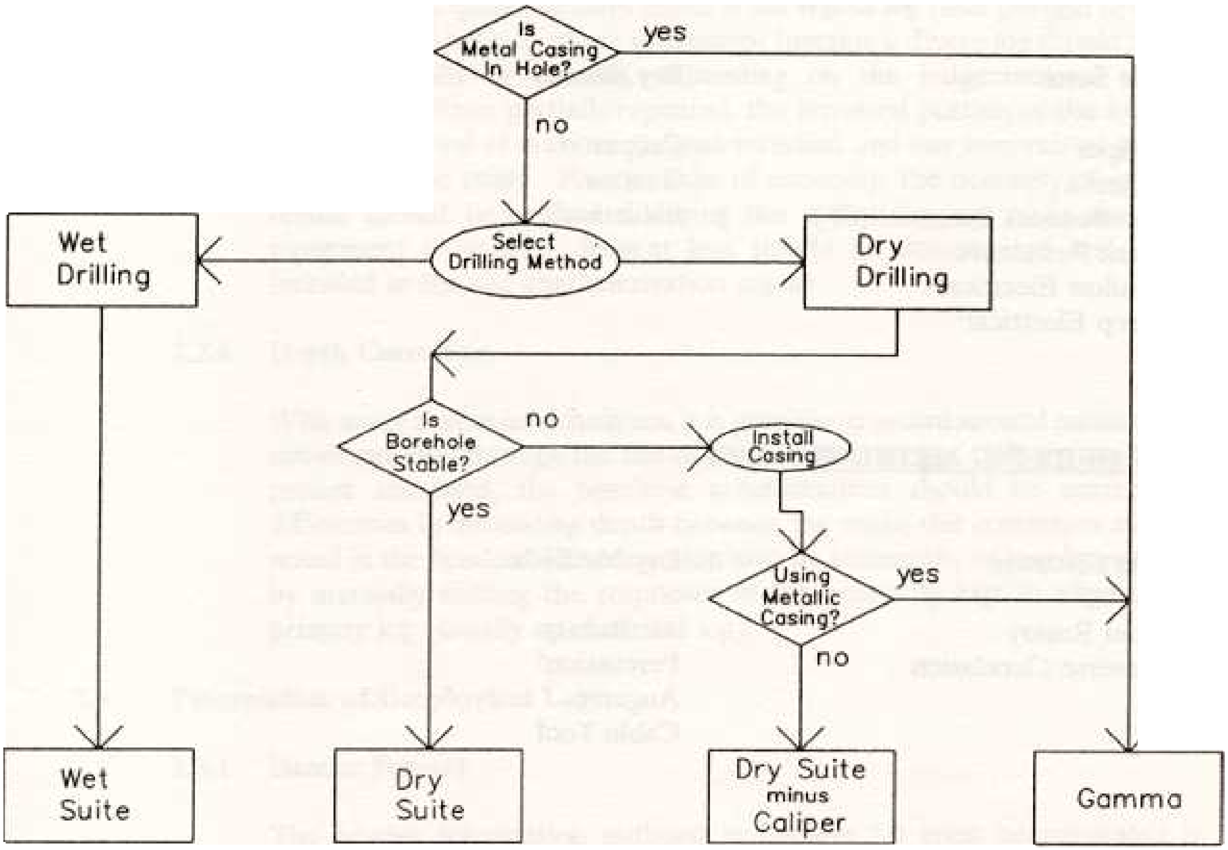


Figure 3. Flow chart outlining the selection process for the basic borehole logging suite. Of primary importance to the selection of borehole geophysical techniques is whether casing is present in the hole at the time of logging. For the purpose of this document, "casing" includes drill pipe and hollow-stem auger pipe.

The selection process in this document for the basic borehole logging suite does not account for the presence of natural ground water in a boring drilled with dry methods. This is an important factor, since a significant thickness of ground water would enable the use of additional wet methods in an otherwise "dry" hole. However, the presence or amount of ground water in a boring is site-specific, and it is not practical to develop selection criteria for this situation. Therefore, it is the responsibility of the qualified geologist or geophysicist on site to document borehole conditions and recommend additional borehole geophysical techniques when necessary.

2.5 Recommended Practices and Specifications for Borehole Logging Techniques

The following guidelines have been developed for those borehole geophysical methods that are widely used in environmental investigations or, in the opinion of the DTSC, have a demonstrated potential for use in hazardous waste investigations. Due to the large number of instruments available, it is not practical to develop guidelines for every borehole logging technique. However, as the use of other techniques increases and new techniques are developed, the guidelines will be updated to meet the state of the science.

2.5.1 Electrical Logs

Electrical logs include all logs that measure differences in electrical potential in and adjacent to the borehole due to the flow of electric current (Keys, 1989). Such logs include spontaneous potential (SP), single-point resistance, resistivity and induction techniques. These logs are used to determine bulk and formation-water resistivity, and determine the invasion profile (Figure 4) of the drilling fluid (often an indicator of permeability). Electrical logs may also be used to determine the porosity of clean sand beds (Archie, 1942; Schlumberger, 1989)

Fluid Sampling. Electrical logs (excluding induction logs) can only be used in liquid-filled, uncased holes. Quantitative interpretation of electrical logs requires knowledge of effects of the drilling fluid, necessitating resistivity measurements of the drilling mud and mud filtrate. Measurements of both the mud and the mud filtrate is preferred, but if mud filtrate values are not available, they may be calculated from the drilling mud resistivity, using the formulas presented by Schlumberger (1984, after Overton and Lipson, 1958). Since resistivity is dependent upon temperature, the temperature of the sample should also be recorded at the time of measurement. Resistivity measurements are usually taken from a circulated sample of the drilling fluid; however, under some cases (such as ground water flow within the borehole) measurement of the entire fluid column may be needed, requiring a separate fluid-conductivity (or fluid-resistivity) log (refer to Keys [1989] for a discussion of fluid-conductivity logs).

Electrical techniques (excluding induction) are seldom used with auger drilling. Auger drilling is designed to eliminate the need for drilling fluids; therefore, the use of electrical logs in augered holes would require filling the bore with liquid (assuming data are needed above the water table), eliminating the advantage of this drilling technique. However, situations may arise where it would be advantageous to run electrical logs in augured holes. In this case, only potable water may be introduced into the hole. If electrical logs are run in augured holes, the resistivity and temperature of the borehole fluid needs to be measured, either by sampling or through a fluid-conductivity log. If sampled, the sample should be taken from the borehole immediately after logging, to minimize potential errors associated with a stratified fluid column.

Spontaneous Potential (SP) Logs. Spontaneous potential (SP) logs detect changes in electrical potential caused by lithologic or water chemistry contrasts within a borehole. SP measurements are commonly used in the oil industry to determine formation water resistivity (R_w; Schlumberger, 1989). However, the empirical formulas used to determine R_w often fail for shallow aquifers, due to highly variable formation-water salinity, the general absence of massive, clean sand, and the presence of cations other than Na^+ in significant amounts. Guyod (1966) has discussed the problem of R_w determination in fresh water from the SP log; Collier and Alger (1988) state that the SP log is quantitatively useful only in thick, clean sands. Therefore, SP logs should be used solely for *qualitative* analysis (a possible exception to this rule would be the case of a flat SP curve; in this case [assuming no malfunction], R_w would be equal to the resistivity of the drilling fluid).

A common problem with SP logs is caused by adjusting the shale (or clay) baseline during the logging procedure (Collier and Alger, 1988). This can generally be avoided by observing SP response while the probe is being lowered in the hole, and adjusting the baseline accordingly prior to recording; however, circumstances may arise where the baseline may need to be shifted during recording. If this occurs, the baseline shift must be clearly marked on the log record, and a new scale should be inserted above the shift.

Resistivity Logs. Many different borehole logging probes are currently available to measure resistivity. Of these tools, point-resistance and normal resistivity probes are most commonly used for ground water studies. Focused or guard logs (that focus current into the formation) are also used, although less frequently than the normal tools.

Both normal and focused resistivity logs are sensitive to borehole mud conditions, bed thicknesses and the thickness of the invaded zone adjacent to the well bore (Schlumberger, 1989). Normal logs may be severely affected. Focused logs are influenced to a lesser degree. In any case, every resistivity log requires corrective processing when used for quantitative analyses (Collier and Alger, 1988).

Focused and normal resistivity logs are generally recorded at short and long electrode spacings, to determine the invasion profile of the drilling fluid. Typical short spacings vary from 8 to 16 inches; long spacings vary from 32 to 84 inches. For the purpose of defining standard spacings of normal logs for use in hazardous waste investigations, short-normal spacings should be no

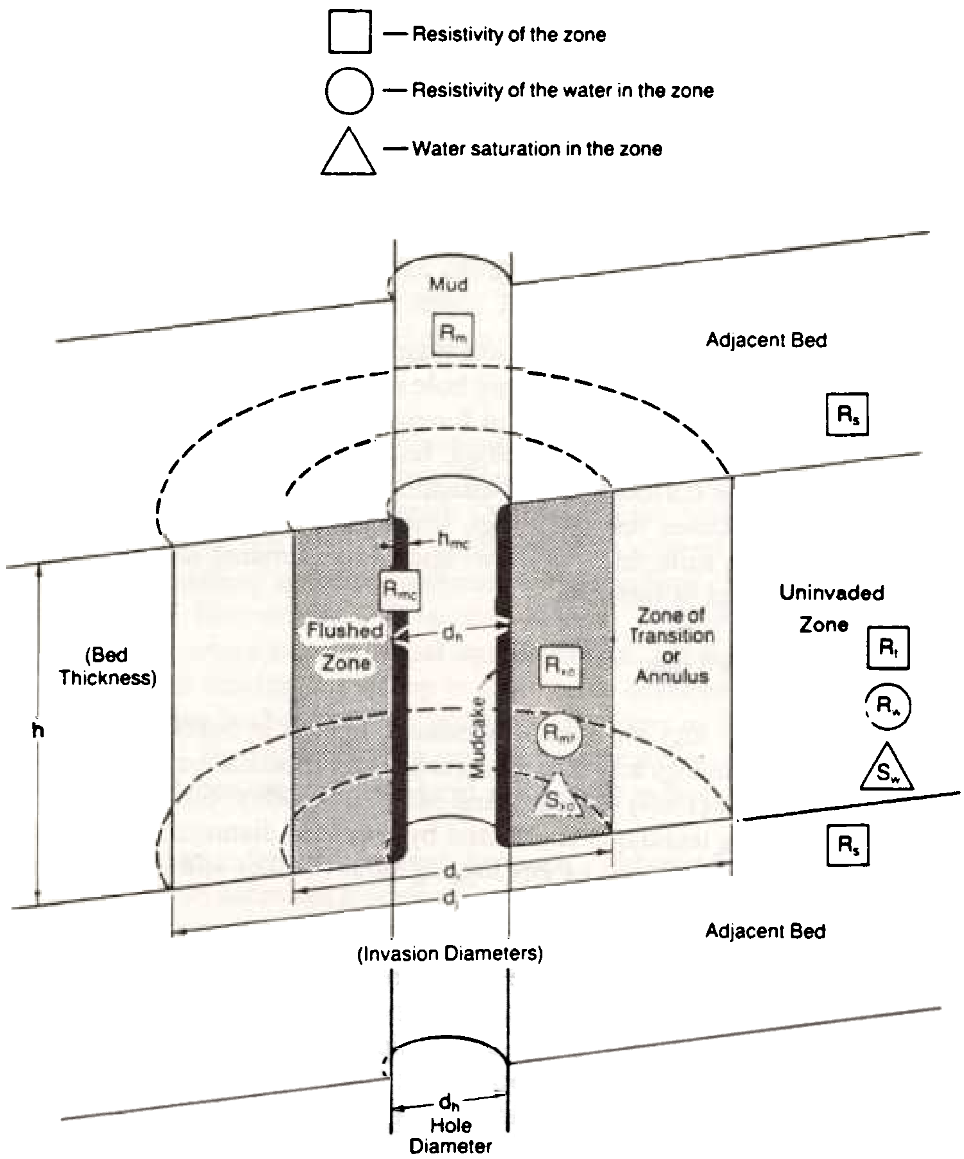


Figure 4. Diagrammatic representation of the invasion profile. Invasion results from infiltration of drilling fluid from the borehole into the surrounding formation. Invasion occurs with the use of "wet" drilling methods. For a definition of abbreviations, see Abbreviations and Symbols. From Schlumberger (1984).

greater than 16 inches. Long-normal spacings should be no greater than 64 inches.

Lateral logs are similar to normal logs, but with an extremely long (up to 18 feet) electrode spacing and a correspondingly deep formation measurement. Lateral logs exhibit an asymmetrical log response that is difficult to interpret, even for relatively thick beds. Where beds are thin, the difficulty of interpretation becomes extreme. Therefore, use of lateral logs is not recommended--if deep information is needed, an appropriate focused log should be used.

Induction Logs. Induction logging techniques are often used in place of resistivity techniques where hole conditions do not permit standard resistivity logging. Like normal and focused resistivity techniques, induction logs are influenced by both lithology, borehole and invasion effects, and therefore must be corrected when quantitative analyses are desired. As with normal and focused resistivity logs, when induction logs are chosen as part of the logging suite, both shallow- and deep-sounding induction probes should be included in the suite.

Caliper Logs

Caliper logs are used to measure changes in borehole diameter. The utility of these logs and their theoretical and practical basis have been discussed by Hilchie (1968) and Keys and MacCary (1983). Since virtually every borehole logging technique is affected by borehole diameter changes, caliper logs are an essential part of any logging suite (Collier and Alger, 1988).

Recommended Specifications. Many caliper tool configurations exist; the primary differences lie in the number of measuring arms and arm type. Multiple arms provide a better indicator of borehole washouts and ellipticity. Because of this advantage, caliper probes used for hazardous waste site investigations should possess at least three mechanical measuring arms of sufficient length to span the expected range of borehole diameter changes.

Three basic caliper arms exist: pads, bow springs and fingers. The type of arm that is used can significantly affect the resolution of the caliper log. Since fingers provide better resolution than pads or bow springs, caliper arms for use in hazardous waste investigations should be of the finger type.

Supplementary Caliper Measurements. For some borehole logging techniques (e.g., nuclear logs), borehole diameter effects are automatically compensated by a built-in caliper. When compensating calipers are part of any borehole technique, a log from the compensation caliper should be recorded in addition to the regular caliper log.

Nuclear Logs

Nuclear logs measure radioactivity within the borehole, either due to natural radioisotopes within the formation or from a transient response to radioactive sources contained within the probe. Four nuclear logging tools are widely used: gamma, gamma spectrometry, gamma-gamma and neutron. Of these, the gamma-gamma and neutron techniques contain radioactive sources. Gamma-gamma is also called a density log--but this log does not directly measure density, so the term gamma-gamma is preferred for discussion purposes.

Regulatory Requirements. There are currently no specific state regulations governing the use of radioisotopes in borehole logging. Within California, use of radioisotopes is enforced under Federal law (Code of Federal Regulations, Title 10, Part 39) by the Radiologic Health Branch of the Department of Health Services, which is responsible for licensing the use of radioisotopes within the state. Under the guidelines of the Radiologic Health Branch, the use of nuclear logs containing radioactive sources is prohibited in potable aquifers (defined as aquifers containing less than 3000 mg/l total dissolved solids). In the case of hazardous waste investigations involving contamination of potable aquifers, the Radiologic Health Branch may grant one-time exemptions to this prohibition at their discretion, depending on hole condition, construction details and other pertinent site information. Any nuclear logging for hazardous waste sites (excluding gamma and gamma spectrometry logging) using active sources must be licensed by and comply with the guidelines of the Radiologic Health Branch, or have the appropriate exemption.

Order in the Logging Sequence. Of prime concern in the use of radioactive sources for logging is the possibility of losing the source within the borehole. To avoid this, active nuclear logs should always be run last, after all other logs have been run and the resulting data have been used to assess borehole conditions for the possibility of hole collapse and/or lodging of the probe in the borehole.

Time Constants/Count Intervals. When analog equipment is used to obtain nuclear logs, the repeatability of the measurements is dependent upon the measurement interval (time constant) and the logging speed. The selection of a time constant that is too short reduces repeatability and makes the data difficult to interpret. On the other hand, increasing the time constant reduces sensitivity and requires a slower logging speed. The time constant must be chosen appropriately on a site-specific basis, but under most conditions it should not exceed 10 seconds.

For digital logging equipment the **count interval** (the time interval over which neutron or gamma events are counted) replaces the time constant. Unlike the time constant, the count interval for most digital instruments is fixed, usually at 1 second (Hallenburg, 1984). This short interval may occasionally limit repeatability, but this deficiency is offset by increased processing and enhancement capabilities provided by the digital format. In general, any count interval of no more than three seconds provides adequate results, and is considered acceptable.

Logging Speed. Logging speed significantly affects data quality. Faster logging speeds reduce sensitivity and cause a lag in the probe response (whereby probe response occurs above or below the true location of the bedding surface). Lag is most pronounced on analog systems (lag also occurs with digital systems, but is generally insignificant; however, depending on the particular configuration of the system in use, lag may become significant at high logging speeds). The appropriate logging speed must be chosen on a site-specific basis, but under most conditions it should not exceed 30 ft/min (Collier and Alger, 1988). For most hazardous waste investigations, this maximum speed is not restrictive. The maximum time required for a single logging run would typically be less than 10 minutes. Even at this speed, lag can be significant and should be corrected.

Units of Measurement. Several different units of measurement are used to quantify the response of nuclear probes to radioactivity. The primary unit used for most nuclear logs is the count per second. The only standardized units of radiation measurement for borehole logging are those developed by the American Petroleum Institute (API, hence these units are called *API units*). API units exist for gamma and neutron logs, but for neutron and gamma-gamma logs, counts per second are usually directly converted to density or porosity units. This is acceptable for those logs, but we recommend that gamma logs be recorded using API units.

With gamma-gamma and neutron logs, the log response is often directly converted to units of density or porosity, respectively. This is an acceptable technique as long as the original data are presented along with the converted values. This requirement is necessary because the conversions are not absolute. Rather, they are based on sets of assumptions and empirical equations that are dependent on lithologic composition and interstitial fluid, and may not always be applicable to specific stratigraphic conditions.

Measurement Through Casing. Gamma-gamma logging techniques measure the attenuation of gamma rays as they pass from a source within the probe through the adjacent formations. Gamma logs, on the other hand, measure natural gamma radiation inherent to the formations. Both gamma and gamma-gamma techniques may be significantly affected by attenuation due to casing materials, filter packs and annular sealants (Keys, 1989). These factors can be corrected to some extent, but the results to date are considered questionable (Collier and Alger, 1988). Quantitative interpretation of gamma and gamma-gamma logs in cased holes is not recommended, with the possible exception of logging through temporary casing (no cement, no filter pack) placed in the hole to prevent loss of the probe. For this case, appropriate attenuation factors and corrections (if available) must be applied. Neutron logs are only minimally affected by casing, and quantitative interpretation of neutron logs made through casing are common. However, cement, filter packs and annular seals adversely affect log response, and quantitative interpretation of neutron logs made through these materials is not recommended.

3 SUMMARY OF GUIDELINES

The following outline is presented to summarize the important points presented in this document.

PERSONNEL QUALIFICATIONS

1. Must use a Registered Geologist or a Registered Geophysicist.
2. Provide a summary of specific borehole geophysical experience.

QA/QC PARAMETERS

1. Define study objectives and rationale for tool selection.
2. Ensure header information is as complete as possible.
3. Document correction procedures.
4. Follow recommended calibration procedures.
5. Use appropriate field standards and perform field checks.
6. Choose appropriate logging speed.
7. Use an accurate surface reference elevation.
8. Provide repeat logs.
9. Correct logs for different depths of measurement.

PRESENTATION OF GEOPHYSICAL LOGS

1. Standardize log and header formats.
2. Overlay no more than two logs on the same track (except for Track 1).
3. Use the same depth scale for every borehole log.
4. Maximum log scale 5"=100'.
5. Present logs at coarse and detailed scales when necessary.

SELECTION OF LOGGING TECHNIQUES

1. Use the basic logging suite (Table 2, page 12) as a starting point for tool selection.
2. Use other logs beyond the basic logging suite (discussed in Section 2.4) as appropriate.

RECOMMENDED PRACTICES AND SPECIFICATIONS FOR BOREHOLE LOGGING TECHNIQUES

ELECTRICAL LOGS (ALL)

1. Measure resistivity of drilling mud and (where applicable) mud filtrate.

SP LOGS

1. Use for qualitative analysis only.
2. Avoid artificial baseline shifts.

RESISTIVITY LOGS

1. Use both shallow- and deep-sounding probes to determine invasion profile.
2. Deep-focused logs are strongly preferred over lateral logs.
3. Apply log corrections for quantitative analysis.

INDUCTION LOGS

1. Use both shallow- and deep-sounding probes to determine invasion profile.
2. Apply log corrections for quantitative analysis.

CALIPER LOGS

1. Use caliper tools that have at least three finger-type feelers.
2. Include accessory caliper logs as part of the log records.

NUCLEAR LOGS

1. Operator must possess a valid DHS permit and exemption for ground water logging.
2. Run nuclear logs last.
3. Use time constant less than or equal to 10 seconds, or a count interval less than or equal to 3 seconds.
4. Use a logging speed less than or equal to 30 feet/minute.
5. Use API units for gamma logs.
6. Provide both raw and converted values from gamma-gamma and neutron logs when used to derive density or porosity.
7. When logging through cement and casing, use nuclear logs for qualitative analysis only.

4 REFERENCES

API (American Petroleum Institute). 1967. Recommended Practice and standard form for electrical logs. API RP 31, American Petroleum Institute, Dallas.

API (American Petroleum Institute). 1974. Recommended Practice for standard calibration and format for nuclear logs. API RP 33, American Petroleum Institute, Dallas.

API (American Petroleum Institute). 1991. Recommended digital log interchange standard (DLIS). API RP 66, American Petroleum Institute, Dallas.

Archie, G.E. 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Petroleum Transactions of the AIME, v. 146, p.54-62.

Asquith, G.B. and Gibson, C.R. 1982. Basic well log analysis for geologists. American Association of Petroleum Geologists, Tulsa, OK, 216 p.

Collier, H.A. and Alger, R.P. 1988. Recommendations for obtaining valid data from borehole geophysical logs. Proceedings of the second National Outdoor Action Conference on aquifer restoration, ground water monitoring and geophysical methods. National Water Well Association, Dublin, Ohio, p. 897-923.

Guyod, H. 1966. Interpretation of electric and gamma-ray logs in water wells. Log Analyst, v. 6, no. 5, p. 29-44.

Hallenburg, J.K. 1984. Geophysical logging for mineral and engineering applications. Penn Well Publishing, Tulsa, OK, p.108-111.

Hilchie, D.W. 1968. Caliper logging - theory and practice. Log Analyst, v. 9, no. 1, p. 3-12.

Hodges, R.E. 1988. Calibration and standardization of geophysical well-logging equipment for hydrologic applications. U.S.G.S. Water Resources Investigations Report 88-4058, 25 p.

Keys, W.S., and MacCary, L.M. 1983. Application of borehole geophysics to water-resources investigations. U.S.G.S. Techniques of Water Resources Investigations, Book 2, Chap. E1, 126 p.

Keys, W.S.. 1989. Borehole geophysics applied to ground water investigations. National Water Well Association, Dublin, Ohio, 313 p.

Overton, H.L. and Lipson, L.B. 1958. A correlation of the electrical properties of drilling fluids with solids content. Petroleum Transactions of the AIME, v. 213, pp.

Schlumberger Limited. 1974. Log interpretation, volume II - applications. Schlumberger Limited, New York, p. 2.

Schlumberger Limited. 1984. Schlumberger log interpretation charts. Schlumberger Well Services, Houston, p. 1.

Schlumberger Limited. 1989. Log interpretation principles/applications. Schlumberger Educational Services, Houston, pp.

INDEX

COMMENT SHEET

As a user of this document, your comments are important. Please use this sheet to inform us of any errors, deficiencies or suggested improvements to this document. If you identify an error or deficiency, please suggest how it can be corrected. Attach additional sheets if necessary. Send your comments to:

California Department of
Toxic Substances Control
P.O. Box 806
Sacramento, CA 95812-0806

Attention: Geological Support

Name: Address:

Name and address are optional, but including them will help us follow-up and address your comments.

Title: Application of Borehole Geophysics at Hazardous Substance Release Sites

Section:
Comment:

Suggested Revision:

Please cut here

95 76256